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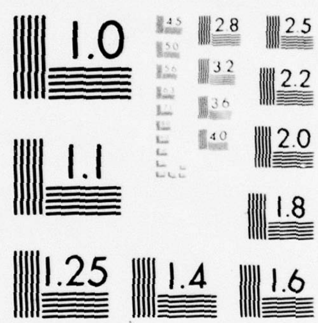

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One Dimensional D.C. Resistivity Due to Strong Low Frequency Turbulence

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Plasma Physics Division

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A theoretical model is presented showing the effects of finite amplitude ion cavities on the d.c. conductivity of a collisionless one-dimensional plasma. A 20% ion cavity is shown to prevent the acceleration of 50% of the plasma electrons. The effect is independent of cavity width and spacing so that in the case of localized, spiky turbulence, rms ion density fluctuations of a few percent can significantly modify the d.c. response. The theoretical predictions are compared with both particle and Vlasov computer simulations.

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CONTENTS

ONE DIMENSIONAL D.C. RESISTIVITY DUE TO STRONG LOW FREQUENCY TURBULENCE

The problem of anomalous plasma d.c. resistivity in one dimension is one of the oldest basic plasma physics questions. Its resolution has eluded the plasma community despite the intensive theoretical and experimental efforts[1,2]. Besides its fundamental nature, the question of anomalous resistivity is of utmost practical importance for laboratory plasma heating and for energy dissipation and particle acceleration in space plasmas[2]. According to our present understanding, the presence of a field aligned electron current in the plasma with a drift velocity v_D, higher than a threshold, excites density fluctuations which then scatter the electrons with a collision frequency ν^* larger than the small angle Coulomb frequency ν, thereby producing a higher dissipation rate. This provides a consistent and experimentally satisfactory picture if $\nu^* > \Omega_e$ where Ω_e is the electron cyclotron frequency. However, when $\nu^* < \Omega_e$ the electron magnetic moment is conserved and the electrons should be treated as one dimensional. In this case, as clearly shown by Petviashvili,[3] the formation of a plateau in the electron distribution function precludes any resistivity enhancement beyond a few percent of the classical value. It is the purpose of this letter to demonstrate that inclusion of strong turbulence effects can remove most of the fundamental difficulties encountered in one-dimensional anomalous resistivity and produce a consistent and satisfactory picture. The basic idea is that density cavities in the ion background cause the existence of low frequency potential barriers. When a d.c. electric field is applied these barriers can prevent the free streaming acceleration of a significant fraction of the electrons.

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An important step forward in understanding when anomalous d.c. resistivity can appear was the observation of Papadopoulos and Coffey[4] that the low frequency density fluctuations could be generated by means other than current driven instabilities. This removes the threshold requirement on v_D of the ambient plasma. In their paper the low frequency fluctuations appeared due to the presence of suprathermal electron beams. Such situations exist both in relativistic beam plasma heating and in the auroras due to the presence of the energetic precipitating electrons. It was noted[4,5] that the presence of the beams creates electron plasma oscillations whose pondermotive force, acting on the plasma, drives low frequency density fluctuations. In going into the one dimensional situation and within the framework of weak turbulence theory the same difficulties reappear as in the current driven case. However under strong turbulence conditions (i.e., $\frac{W}{nT} > (k\lambda_D)^2$), the density fluctuations have been shown to form large localized density cavities (cavitons) in which the high frequency field is trapped (solitons)[6,7]. Figure 1 shows a typical structure as seen in a computer simulation of such cavities produced by the high frequency (ω_{pe}) waves due to the existence of a beam.

While our original work centered on such beam-generated cavities which occur in many situations of current physical interest, the basic physical effects noted in this letter will appear whenever finite amplitude ion cavities exist in the ambient plasma. A description of the interaction of the background electrons with the cavities requires a local theory going beyond the limit of weak-turbulence quasi-linear wave-particle interaction. In view of the analytical complexity of the subject we present below a phenomenological theory supplemented by computer simulations.

THEORY

Assume that there is a density cavity in the ion background with a depth $\delta n_i/n_o$ (n_o is the average ion density. The local density is $n_i(x) = \left[1 - \frac{\delta n_i}{n_o}\right] n_o$). In order to maintain

charge neutrality at low frequency, there must exist a low frequency potential internal to the plasma, $\delta\phi$, large enough to exclude a fraction of the electrons equal to δn_i. This means that inside the cavity

$$\left(1 - \frac{\delta n_i}{n_o}\right) n_0 = \int_{-\infty}^{\infty} f_{e,in}(\mathrm{v})\, d\mathrm{v}. \tag{1}$$

From the Vlasov equation, since f is constant along lines of constant energy we can determine $f_{e,in}$ in terms of $f_{e,out}$. If $f_{e,out}$ is a nondrifting Maxwellian then $(1 - \delta n_i/n_o) = e^{-\delta\phi/2}$ where $\delta\phi$ is normalized to the electron thermal energy and $\mathrm{v}_{te} \equiv 1$. Defining a trapping velocity $\mathrm{v}_{tr}^2 \equiv \delta\phi$, the fraction of trapped electrons is

$$\frac{\delta n_e}{n_o}\Big|_{tr} = \sqrt{\frac{2}{\pi}} \int_0^{\mathrm{v}_{tr}} e^{-\mathrm{v}^2/2}\, d\mathrm{v}.$$

This is plotted on Fig. 2 as a function of cavity depth. In the absence of any cavities, the electrons will free stream with an average velocity $\mathrm{v}_{fs}(t) = \frac{q}{m} Et$ when an external d.c. field is applied. The presence of the density cavities divides the electrons into two classes. The central part of the distribution with $|\mathrm{v}| < \mathrm{v}_{tr}$ does not accelerate, since it is reflected by the potential barriers. The tail with initial velocities parallel to v_{fs} being untrapped is displaced by v_{fs}; untrapped particles that have an initial velocity opposite to v_{fs} can only slow down to a velocity $\mathrm{v}_{min} = (\delta\phi)^{1/2}$. At that point they are scattered by 180° by the potential. This means that the electrons in the left-hand tail have undergone a sudden increase in velocity equal to 2 v_{min}. Therefore, the average electron drift velocity is

$$\mathrm{v}_D = \left(1 - \frac{\delta n_e}{n_o}\Big|_{tr}\right) \mathrm{v}_{fs} + 2\mathrm{v}_{min} \int_{\mathrm{v}_{min}}^{\mathrm{v}_{min}+\mathrm{v}_{fs}} \frac{d\mathrm{v}}{\sqrt{2\pi}}\, e^{-\mathrm{v}^2/2}. \tag{2}$$

SIMULATION RESULTS

We present here a series of 1D computer simulations showing the acceleration of a plasma by a constant d.c. electric field. A particle-fluid hybrid code[7] and a Vlasov simulation

code[8] were used. In the first group of simulations we imposed a fixed ion density fluctuation on the plasma. This allowed us to vary easily $\delta n_i/n_o$ and the shape of the fluctuation in order to assess their effect. In the second group of simulations, the ion fluctuations were generated self consistently by the pondermotive force of a high frequency long wavelength pump, such as expected in the presence of weak electron beams or a laser.

Figure 3 shows the results of the first set of runs. The straight line is the free streaming velocity of the plasma and occurs when $\delta n_i = 0$. The curved lines are calculated from equation 2 assuming $v_{min} = v_{tr}$. Three of the simulations plotted used the particle fluid hybrid code. The electrons were particles. The ions were a fixed fluid background. The small differences of the simulations with the theoretical curves can be attributed to the electron noise due to the finite number of particles. As can be seen in Fig. 3 this was actually confirmed by using the noise free Vlasov code with $m_i = \infty$. This code due to its noise free property allowed us to clearly distinguish between trapped and untrapped electrons. Figure 4 shows the electron distribution at $t = 0$ and $\omega_{pe}t = 750$. With $\delta n_i/n_o = .2$, 50% of the particles were trapped in agreement with the theory. Whitfield and Skarsgard[9] observed this splitting of the electron distribution function in particle simulations in which they modelled the effect of a bumpy magnetic field with a fixed sinusoidal density variation.

We initialized the ions in the Vlasov simulation four different ways ($n_i(x) = n_o(1 + (\delta n_i/n_o)\sin kx)$); (1) $k = 2\pi/L$. (2) $k = \pi/L$. (3) $k = \pi/L$, $n_i(x) = n_o$ for $x \leqslant L/2$. (4) $k = \pi/L$, $n_i = n_o$ for $x \leqslant 3L/2$ (only a cavity). L, the grid length, equals 50 λ_D. $\delta n_i/n_o = 0.2$ in all four cases. It was found that the interaction was independent of both the width and the spacing of the cavities and dependent only on the value of the density minimum. These results are consistent with the simplified theory presented previously.

We examined next two situations where the ion cavities are self consistently generated due to the OTSI.

Figure 5 shows the results of a hybrid simulation with $m_i = 128 m_e$ where a kinetic beam plasma instability with growth rate $\gamma = .006\omega_{pe}$ and phase velocity $v_{ph} = 81 v_{te}$ was driven. The mode was nonlinearly stabilized[5-7] by creating a set of 10 density cavities (see Figure 1). The rms value of the density fluctuations was 15%, while the localized cavity depth was .2-.3. An electric field was turned-on at $\omega_{pe} t = 700$. It can be seen that the value of the acceleration was substantially smaller than free streaming.

In another run the Vlasov code was used with a constant dipole pump of energy $\frac{E_o^2}{8\pi n_p T_{eo}} = .1$. Such a run simulates the possibility of a microwave or laser pump at ω_{pe} across the current carrying system. A large single cavity was formed in this case. The plasma response was again consistent with the simple theoretical picture.

SUMMARY AND CONCLUSIONS

The results of this letter should be considered as a preliminary but major step in understanding and modeling the long times anomalous resistivity in one dimension. Referring first to our self consistent results of the second simulation group we demonstrated that

(a) In the presence of electron beams or externally imposed high frequency (ω_{pe}) electromagnetic fields, large local density cavities ($\delta n/n_o \simeq .2 - .6$) can be formed.

(b) The potentials associated with these cavities are large enough to trap a significant fraction of the thermal electrons, so that the entire current will be carried by a small fraction

of untrapped electrons. This effect will experimentally appear as an enhanced resistance and the appearance of localized runaway beams. The long time scale behavior of the system will depend on how these beams are thermalized. A possible mechanism is further two stream interaction of the runaways with the trapped electrons. This process will depend critically on the spacing among cavities and is presently under study.

Furthermore the results of the first simulations demonstrated that similar resistivity will appear anytime an instability can create finite amplitude density fluctuations. The ion cyclotron instability seems to be a good candidate and is currently under study. In the presence of an electron current, the generation of ion cavities will disrupt the current. By recalculating Eq. (2) using a drifting Maxwellian one obtains a formula in agreement with preliminary computer simulations.

In concluding we mention that these concepts can help in understanding return current heating in beam plasma interactions and extend the Papadopoulos-Coffey anomalous resistivity in the auroral zones to regions where $\omega_{pe}/\Omega_e \simeq 1$. The results of the constant pump runs suggest the possibility that a laser created corona with large cavities a pellet, can produce short electron beam deposition lengths for *e*-beam-pellet fusion.

We would like to thank Dr. David Book for the use of the Vlasov simulation code. This work was supported by the Office of Naval Research. Part of the simulation work was funded by a research grant from the Naval Research Laboratory Research Computation Center.

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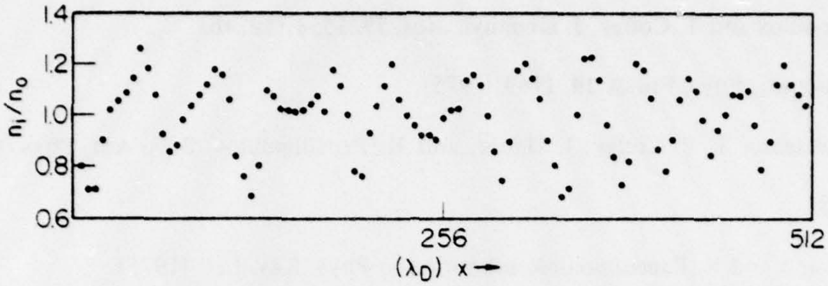

Fig. 1 – Typical ion density fluctuations generated by presence of high velocity *e* beam as seen in computer simulation.

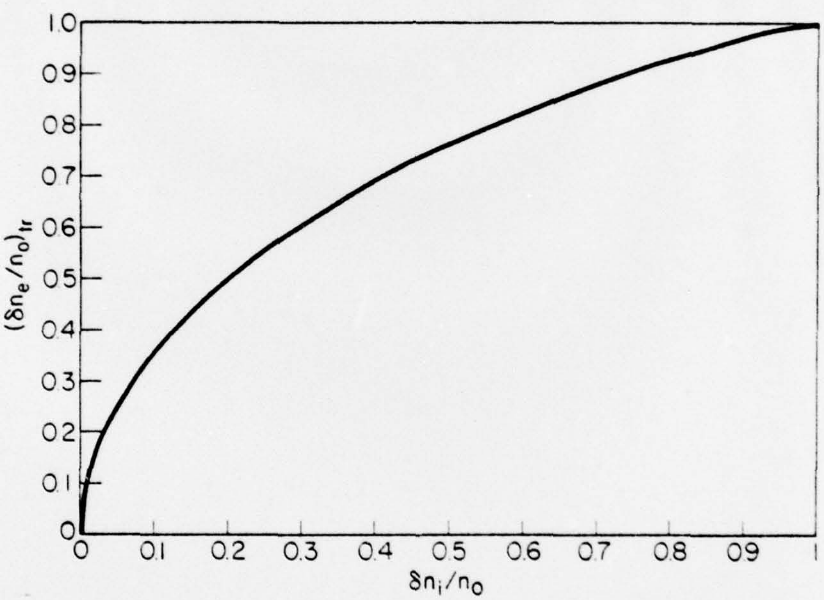

Fig. 2 – Fraction of electron population trapped by ion cavity of depth δn_i. Note cavity of depth .2 traps approximately half of the electrons.

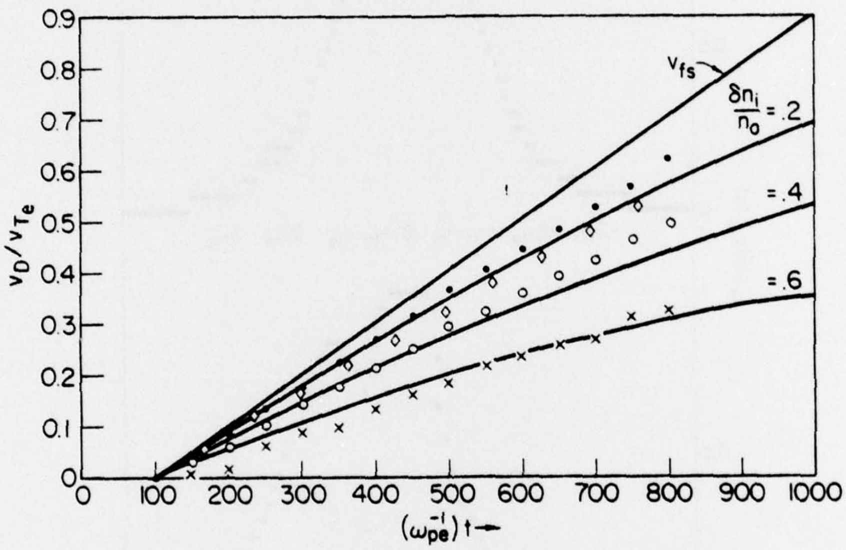

Fig. 3 – Electron drift velocity due to a constant d.c. field. The top line is the free streaming response of the electrons. The three lower lines are the theoretical predictions for different cavity depths. "•", o, x are particle fluid simulations for $\delta n_i/n_o$ = .2, .4, .6. The diamond is a Vlasov simulation for $\delta n_i/n_o$ = .2.

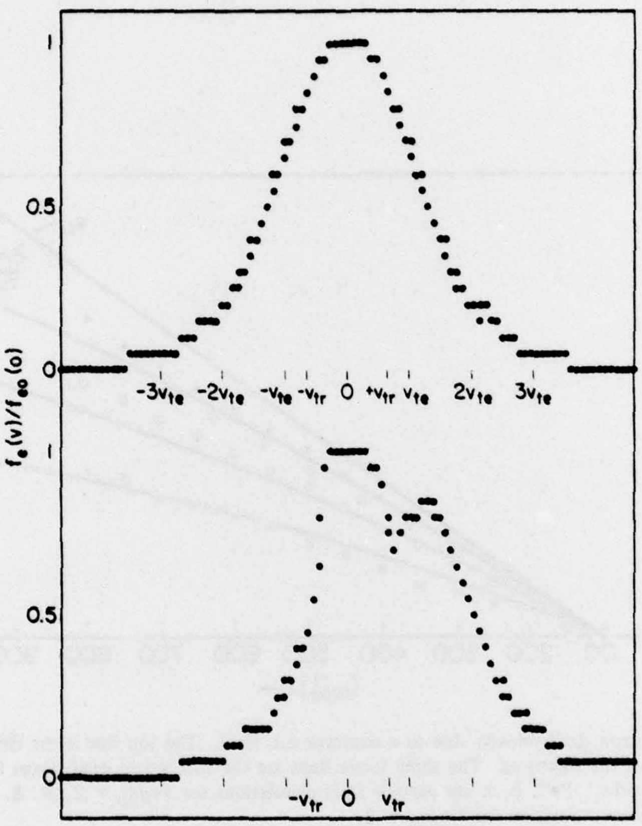

Fig. 4 – Electron distribution from Vlasov simulation shown in Figure 4. $\delta n_i/n_o$ = .2, t = 0 and 750 ω_{pe}^{-1}. Theoretically predicted v_{tr} is marked on scale.

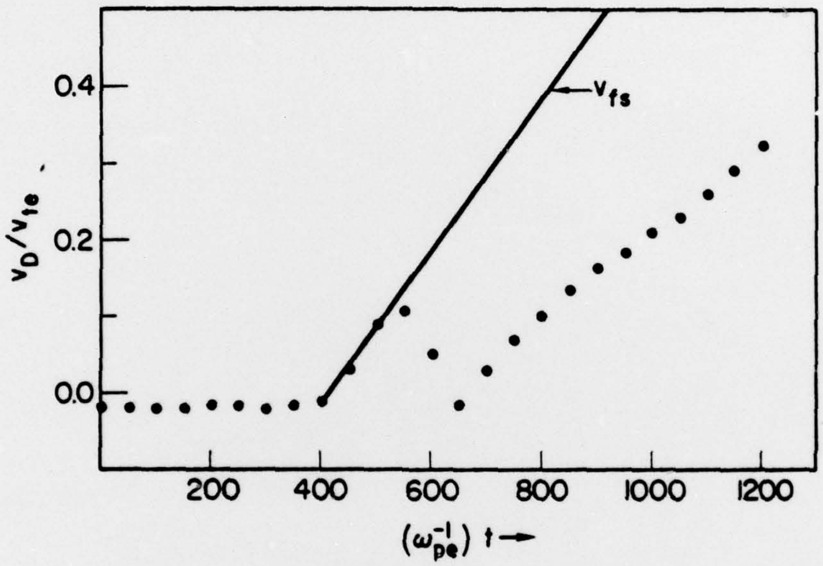

Fig. 5 – D.C. response of plasma with a beam present. Ion background at 400 ω_{pe}^{-1} shown in Figure 1. Note that fluctuations here are generated self consistently.